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EFFECT OF WING LEADING-EDGE SLOTS ON THE SPIN AND RECOVERY CHARACTERISTICS OF AIRPLANES

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SUMMARY

An investigation has been made in the NACA 15-foot free-spinning tunnel to determine the effect of wing leading-edge slots on spin and recovery characteristics. Results obtained from these tests establish a criterion from which the adverse or favorable effects of slots may be predicted from a nondimensional mass-distribution parameter.

The results indicate that, for single-engine designs with mass distributed heavily along the wings and for multiengine designs, recovery will be slower with slots open than with slots closed and the spin will be flatter and at a lower rate of descent. If the mass is distributed heavily along the fuselage, however, recovery will be more rapid with slots open than with slots closed when the elevator is neutral or down, although there will be little apparent effect when the elevator is full up. There will be little effect upon the angle of attack or rate of descent when slots are open and when the mass is distributed heavily along the fuselage.

The slots, when open, will depress the inboard wing of an airplane regardless of loading.

INTRODUCTION

The use of leading-edge slots on the wings of certain types of American airplane to improve the stalling characteristics or to increase the speed range has recently increased. Indications that slots may have a large influence on the behavior of an airplane in a spin have been reported in references 1 to 5. These references indicate that the effect of slots may be either detrimental or beneficial but do not provide means for predicting the effect for a particular condition unless the spin characteristics of the airplane without slots are definitely known. The investigation in the NACA 15-foot free-spinning tunnel reported in the present paper was undertaken in an attempt to relate the effect of slots on spin and recovery characteristics to the mass distribution of the airplane.

Five models of recent airplanes of widely different types, all having slots, were tested with the slots both open and closed. The mass distributions were varied to cover a wide range of loadings from a single-engine mass distribution with mass distributed chiefly along the fuselage to a multiengine mass distribution with mass distributed chiefly along the wings. The effects of the slots on the steady-spin and recovery characteristics were determined.

APPARATUS AND TESTS

The airplanes represented by the five models used for the investigation are briefly described in table I and photographs of the models are given as figures 1 to 5. The models were constructed of balsa and were ballasted for the desired loading conditions by the installation of lead weights at suitable locations. A clockwork mechanism was installed to actuate the recovery control.

The leading-edge slots on the models were of both the partial-span and the full-span types. Comparative tests were made of the slot-open and slot-closed conditions for each loading condition. The center of gravity for each model was kept in the same position during the mass-distribution changes although the total mass varied a small amount.

The NACA 15-foot free-spinning tunnel and spin-testing technique are described in detail in reference 6. Briefly, the models, with the rudder set for a spin, are launched by hand with rotation and in a spinning attitude into the vertical upward air stream of the tunnel. The airspeed of the tunnel is adjusted to equal the rate of descent of the model; the model is thus kept at a fixed height for observation and measurements until recovery is attempted. During the steady spin observations are made of the angle α between the thrust axis and the vertical which is approximately equal to the angle of attack; the angle ϕ between the span axis and the horizontal; the angular velocity Ω about the spin axis; and the rate of descent V.

Recovery is attempted by full and rapid reversal of the rudder. The turns for recovery are taken as the number of turns made by the model from the time the rudder is reversed until the spin rotation ceases. The leading-edge slots were considered to have a "favorable" effect when the number of turns for recovery was less with the slots open than with the slots closed.

RESULTS

The quantitative results of the investigation are presented in tables II and III. Table II shows the steady-spin data and table III, the recovery data. The slot effects are presented qualitatively in figure 6 and in tables IV and V.

The data presented in tables II and III are believed to represent the true model values within the following limits:

α, degrees	± 1
ϕ, degrees	± 1
V, percent	± 2
Ω, percent	± 2
Turns for recovery	$\pm \frac{1}{4}$

All spins were made to the right and positive values of the angle of wing tilt ϕ indicate that the right - that is, the inner - wing is down.

DISCUSSION

The influence of mass distribution upon the effect of slots on recovery was somewhat more evident for the spins when both elevator and ailerons were neutral; accordingly, these results were first plotted (fig. 6) to show the influence of each of the three inertia moment parameters

$\frac{I_X - I_Y}{mb^2}$, $\frac{I_Y - I_Z}{mb^2}$, and $\frac{I_Z - I_X}{mb^2}$. Figure 6 indicates that, although partial separation of the favorable and the adverse effects of slots may be obtained by consideration of the inertia pitching-moment parameter $\frac{I_Z - I_X}{mb^2}$ or of the inertia rolling-moment parameter $\frac{I_Y - I_Z}{mb^2}$, practically complete separation of the effects can be obtained when the inertia yawing-moment parameter $\frac{I_X - I_Y}{mb^2}$ is considered. The same condition was found for aileron and elevator effects in reference 7. The inertia yawing-moment parameter depends on the relative loading along the fuselage and wings; the value of this parameter increases algebraically when mass is added along the wings or removed along the fuselage. Figure 6 shows that the reversal from an adverse to a favorable slot effect occurred at a value of the parameter of approximately -80×10^{-4}.

As a result of the indications of figure 6, tables IV and V were prepared to compare the qualitative recovery data on the basis of the inertia yawing-moment parameter. In table IV, the data are arranged to show the effect of slots for loading variations of the individual models; whereas in table V the data are grouped together for all models. These data indicate that, for the models of which the spin characteristics were investigated for more than one mass distribution, the slot effect tended to become adverse as the value of $\frac{I_X - I_Y}{mb^2}$ was algebraically increased. As the value of $\frac{I_X - I_Y}{mb^2}$ became algebraically smaller, the open slots tended to have a favorable effect when the elevator was neutral or down and to have little effect when the elevator was full up. The fact that separation of favorable and adverse effects is not complete indicates that mass distribution, although a primary factor, is not the sole factor which determines slot effect. For elevator-up configurations, for example, the critical value of the parameter appears to be shifted to a larger negative value than for the elevator-neutral and elevator-down configurations. In some cases when recoveries with slots closed were either extremely rapid or extremely slow, the effect of opening the slots was not noticeable. This fact accounts for the occurrence of a large proportion of the neutral effects at either end of the mass-parameter scale.

The results are interpreted as indicating that open slots will retard recovery for airplanes with mass distributed chiefly along the wings - that is, multiengine airplanes or single-engine airplanes with armament or fuel located in the wings - and that the effect may be of serious magnitude. If the mass distribution is sufficiently light along the wings and heavy along the fuselage, open slots will generally assist recovery when the elevator is reutral or down and will have little effect when the elevator is full up.

The effect of slots on the steady-spin parameters, as shown by a study of table II, appears to be a change of angle of wing tilt which leads to lowering of the inboard tip when the slots are open. This effect occurred regardless of loading, control setting, and individual model characteristics. For loading conditions for which $\frac{I_X - I_Y}{mb^2}$ was algebraically greater than approximately -80×10^{-4}, open slots tended to flatten the spin and to decrease the vertical velocity. For loadings for which $\frac{I_X - I_Y}{mb^2}$ was algebraically less than approximately -80×10^{-4}, open slots had only a small effect upon angle of attack and vertical velocity.

In general, it may be said that, for both recoveries and steady spins, the adverse effects were of larger magnitude than were the favorable effects. No consistent trend of the effect of slots on the angular velocity was noted.

CONCLUSIONS

From tests in the NACA 15-foot free-spinning tunnel of five models of recent airplanes having slots on the leading edges of the wings, the following conclusions are indicated:

1. Leading-edge slots, either partial or full span, may seriously affect the recovery from the spin. The effect may be either adverse or favorable depending on the mass distribution of the airplane.

2. The adverse or favorable slot effect may be generally predicted from design data by use of a nondimensional mass-distribution parameter.

3. For single-engine designs with mass distributed heavily along the wings and for multiengine designs, open slots will have an adverse effect on spin recoveries. For single-engine designs heavily loaded along the fuselage, open slots will generally improve spin recoveries when the elevator is neutral or down; there will be only little effect when the elevator is full up.

4. Open slots will tend to depress the inboard wing in a spin, regardless of mass distribution. For mass distributions for which open slots have an adverse effect on recovery, the spin will be flatter and the rate of descent lower with slots open than with slots closed. For mass distributions for which open slots are favorable to recovery, there will be only little effect upon the steady spin when the slots are opened.

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TABLE I

MOMENTS OF INERTIA OF AIRPLANES

REPRESENTED BY MODELS

Model	Type of airplane	Airplane wing span, b (ft)	Type of slot	Full-scale moment of inertia about body axis (slug-ft^2)			Basic loading $\frac{I_X - I_Y}{mb^2}$ (a)
				I_X	I_Y	I_Z	
1	Pursuit low wing	34.3	Tip, each 37 percent of semispan	3285	5,540	8,550	-91×10^{-4}
2	Scout bomber low wing	50.0	Tip, each 29 percent of semispan	8150	13,475	20,470	-48
3	Observation high wing	40.8	Full span	3705	4,970	7,580	-48
4	Scout observation landplane midwing	33.0	Full span	2958	8,739	10,715	-244
5	Observation scout seaplane biplane	[b]36.0	Full span	3610	5,710	7,070	-98

[a]Symbol m denotes mass of airplane.
[b]Upper wing.

TABLE II

EFFECT OF SLOTS ON STEADY-SPIN CHARACTERISTICS

[All spins made to the right; all values of V given in fps (full scale); α and ø, in deg; Ω in radians/sec (full scale)]

Model	Loading (a)	$\frac{I_X - I_Y}{mb^2}$	Slots	Ailerons with Elevator											
				Up				Neutral				Down			
				V	α	ø	Ω	V	α	ø	Ω	V	α	ø	Ω
1	A	-91×10^{-4}	Closed	Velocity too high to test				Velocity too high to test				Velocity too high to test			
			Open	Oscillatory wandering				Oscillatory wandering				Velocity too high to test			
1	B	-61	Closed	Oscillatory wandering				Velocity too high to test				Velocity too high to test			
			Open	177	--	-	----	---	--	-	----	183	40	8	3.12
1	C	-22	Closed	---	--	-	----	---	--	-	----	205	32	2	4.39
			Open	171	55	7	3.19	---	--	-	----	169	53	6	3.54
1	D	10	Closed	189	48	4	2.81	---	--	-	----	---	--	-	2.83
			Open	171	57	5	3.22	---	--	-	----	161	54	5	3.54
2	A	-48	Closed	Oscillatory wandering				266	21	5	4.55	229	24	0	4.68
			Open	---	--	-	----	---	--	-	----	---	--	-	----
3	A	-48	Closed	185	35	7	2.24	173	35	2	3.35	165	35	0	3.50
			Open	144	52	7	2.70	130	56	3	3.20	124	57	3	3.34
4	A	-244	Closed	No spin				Velocity too high to test				Velocity too high to test			
			Open	No spin				No spin				No spin			
5	A	-99	Closed	---	--	-	----	156	25	7	4.06	---	--	-	----
			Open	---	--	-	----	---	--	-	----	---	--	-	----

Model	Loading (a)	$\frac{I_X - I_Y}{mb^2}$	Slots	Ailerons neutral Elevator											
				Up				Neutral				Down			
				V	α	ø	Ω	V	α	ø	Ω	V	α	ø	Ω
1	A	-91×10^{-4}	Closed	240	29	0	2.52	189	41	1	3.20	199	38	0	3.53
			Open	187	49	6	2.45	181	42	4	3.16	224	34	3	3.89
1	B	-61	Closed	230	31	0	2.71	199	40	-1	3.08	205	36	-1	3.62
			Open	185	50	4	2.56	---	--	--	----	175	46	4	3.14
1	C	-22	Closed	232	33	0	2.92	---	--	--	----	203	32	-3	4.33
			Open	173	52	3	3.13	---	--	--	----	167	51	4	3.32
1	D	10	Closed	244	43	4	2.83	---	--	--	----	226	33	0	4.23
			Open	173	55	3	3.13	---	--	--	----	165	52	3	3.32
2	A	-48	Closed	182	39	1	2.52	164	46	-3	2.88	160	47	-3	3.10
			Open	---	--	--	----	---	--	--	----	---	--	--	----
3	A	-48	Closed	201	28	-3	2.82	177	34	-6	3.44	161	37	-8	3.42
			Open	156	48	2	2.60	128	57	-2	3.20	118	60	-2	3.32
4	A	-244	Closed	No spin				199	23	-1	3.67	143	42	-2	2.71
			Open	No spin				No spin				No spin			
5	A	-99	Closed	129	46	-2	2.72	[b]120	[b]47	[b]-1	[b]3.34	118	49	0	3.48
			Open	---	--	--	----	[b]130	[b]40	[b]4	[b]3.25	---	--	-	----

Model	Loading (a)	$\frac{I_X - I_Y}{mb^2}$	Slots	Ailerons against Elevator											
				Up				Neutral				Down			
				V	α	ø	Ω	V	α	ø	Ω	V	α	ø	Ω
1	A	-91×10^{-4}	Closed	214	--	---	2.64	195	38	-4	3.32	201	36	-4	3.50
			Open	187	40	0	----	179	43	2	2.98	187	--	---	----
1	B	-61	Closed	218	36	-3	2.62	201	36	-4	3.26	207	32	-5	3.53
			Open	189	48	0	2.54	---	--	--	----	185	36	0	3.13
1	C	-22	Closed	Velocity too high to test				---	--	--	----	Velocity too high to test			
			Open	177	37	0	2.89	---	--	--	----	189	37	-1	3.55
1	D	10	Closed	Velocity too high to test				Velocity too high to test				Velocity too high to test			
			Open	185	47	1	2.89	---	--	--	----	189	47	0	3.49
2	A	-48	Closed	178	43	-3	2.36	158	48	-5	2.82	148	49	-4	2.94
			Open	---	--	--	----	---	--	--	----	---	--	--	----
3	A	-48	Closed	211	24	-11	1.95	No spin				165	33	-17	3.44
			Open	160	43	1	2.50	132	57	-3	3.13	128	57	-4	3.20
4	A	-244	Closed	136	53	-6	2.02	129	53	-6	2.24	126	54	-6	2.52
			Open	128	55	-2	1.90	124	52	-3	2.32	121	50	0	2.42
5	A	-99	Closed	---	--	--	----	118	50	0	3.34	---	--	--	----
			Open	---	--	--	----	---	--	--	----	---	--	--	----

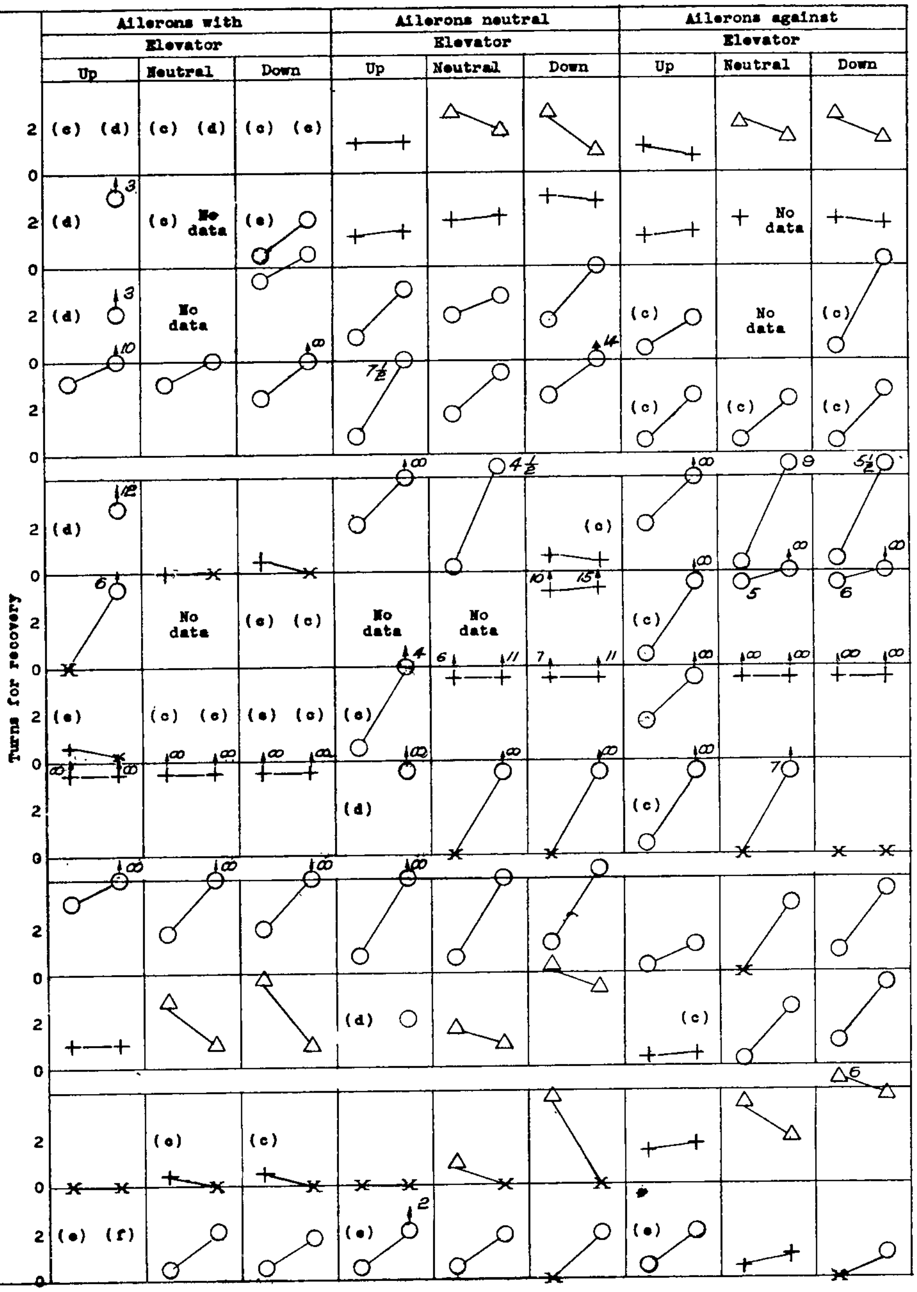
[a]Basic loading denoted by A; variations by B, C, and D.

[b]Recoveries from this spin are $1\frac{3}{4}$ turns with slots closed, 1 turn with slots open.

TABLE III.- EFFECT OF SLOTS ON RECOVERIES[a]

[All recoveries attempted by full rudder reversal - full with to full against]

Model	Loading (b)	$\frac{I_X - I_Y}{mb^2}$
1	A	-91×10^{-4}
1	B	-61
1	C	-22
1	D	10
2	A	-48
2	B	-78
2	C	-143
2	D	74
3	A	-48
3	B	-159
4	A	-244
4	B	-14



[a]Notation used throughout as follows: (1 block = 10/40")

(1) Left-hand symbol denotes slots closed; right-hand symbol, slots open.

(2) Slots adverse to recovery when h > $\frac{1}{2}$ turn.

(3) Slots show no effect on recovery when h < $\frac{1}{2}$ turn.

(4) Slots favorable to recovery when -h > $\frac{1}{2}$ turn.

(5) Y Arrowed symbol denotes no recovery in Y turns.

(6) X Model would not spin.

[b]Basic loading denoted by A; variations, by B, C, and D.

[c]Velocity too high to test. (Considered to recover in not more than 1/2 turn.)

[d]Spin wandering and oscillatory.

[e]Spin steep, wandering, and oscillatory. (Considered to recover in not more than 1/2 turn.)

[f]Spin wandering.

TABLE IV. - SLOT EFFECT[1] FOR VARIED MASS DISTRIBUTION

Control		Model											
Ailerons	Elevator	1				2				3		4	
With	Up	○	—	—	—	+	—	○	+	○	+	—	+
	Neutral	○	—	—	—	+	+	—	+	○	△	○	+
	Down	○	○	○	+	+	+	+	+	○	△	○	+
Neutral	Up	○	○	+	+	—	○	—	○	○	—	○	+
	Neutral	○	○	+	△	○	○	—	+	○	△	○	△
	Down	○	○	+	△	○	+	+	+	○	△	○	△
Against	Up	○	○	+	+	○	○	○	○	○	+	○	+
	Neutral	○	—	—	△	○	○	○	+	○	○	○	△
	Down	○	○	+	△	+	○	○	+	○	○	○	△
Loading (2)		D	C	B	A	D	A	B	C	A	B	B	A
$\frac{I_X - I_Y}{mb^2}$		10	-22	-61	-91	74	-48	-78	-143	-48	-159	-14	-244×10^{-4}

[1]Effect of slots on recovery - adverse denoted by o; none, by +; favorable, by Δ; incomplete data, by ——.

[2]Basic loading denoted by A; variations, by B, C, and D.

TABLE V. - ADVERSE OR FAVORABLE SLOT EFFECT[1] AS DETERMINED BY THE MASS-DISTRIBUTION PARAMETER $\frac{I_X - I_Y}{mb^2}$

Control		Model (2)												
Ailerons	Elevator	2	1	4	1	3A	2A	1	2	1A	5	2	3	4A
With	Up	+	o	—	—	o	—	—	o	—	—	+	+	+
	Neutral	+	o	o	—	o	+	—	—	—	—	+	Δ	+
	Down	+	o	o	o	o	+	o	+	+	—	+	Δ	+
Neutral	Up	—	o	o	o	o	o	+	—	+	—	o	—	+
	Neutral	o	o	o	o	o	o	+	—	Δ	Δ	+	Δ	Δ
	Down	o	o	o	o	o	+	+	+	Δ	—	+	Δ	Δ
Against	Up	o	o	o	o	o	o	+	o	+	—	o	+	+
	Neutral	o	o	o	—	o	o	—	o	Δ	—	+	o	Δ
	Down	+	o	o	o	o	o	+	o	Δ	—	+	o	Δ

80 40 0 -40 -80 -120 -160 -200 -240×10^{-4}

$\frac{I_X - I_Y}{mb^2}$

[1]Effect of slots on recovery - adverse denoted by o; none, by +; favorable, by Δ; incomplete data, by —.

[2]Basic loading denoted by A.

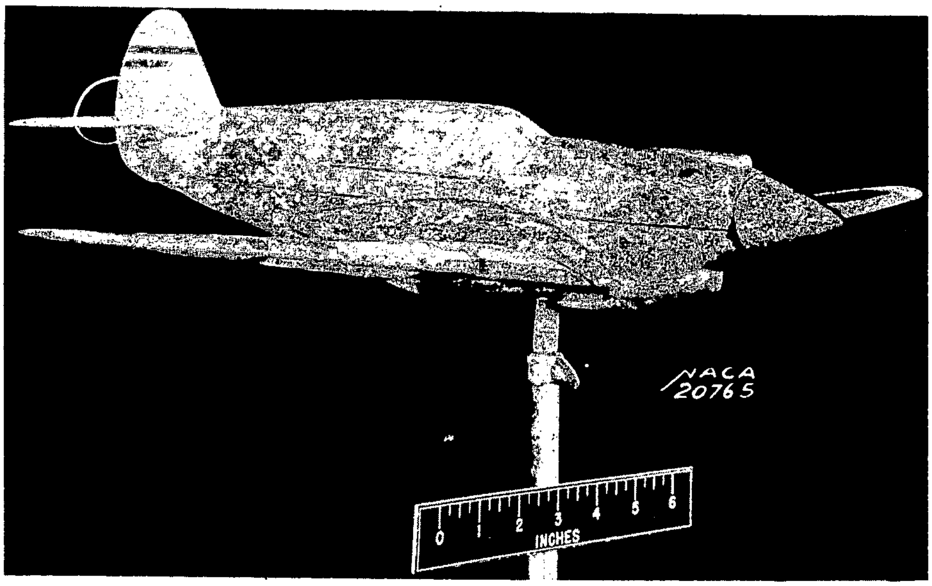


Figure 1.- Model 1. A 1/20-scale model of the Curtiss XP-46 airplane.

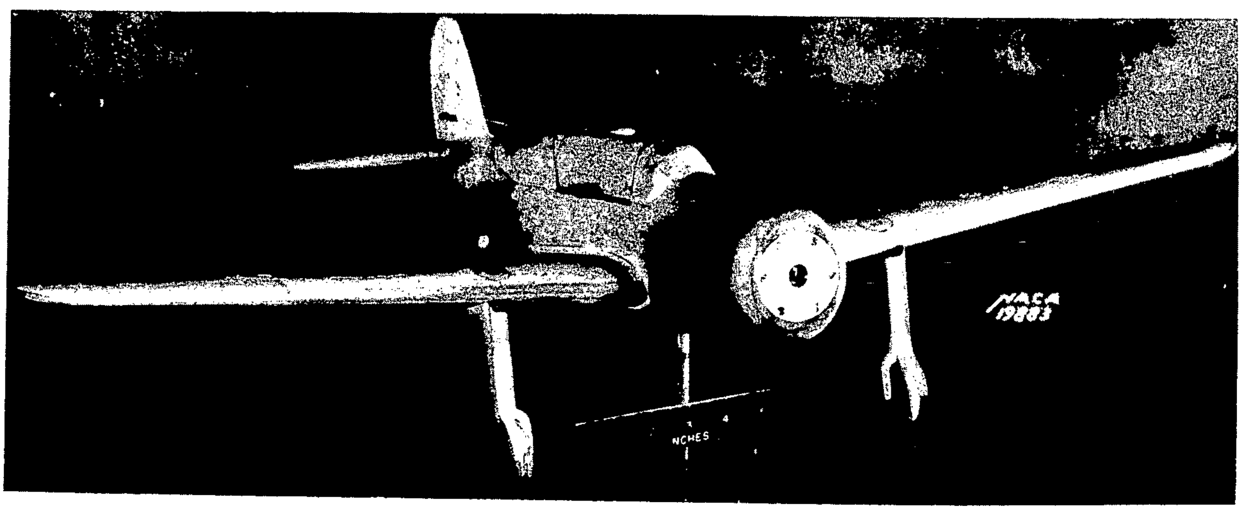


Figure 2.- Model 2. A 1/20-scale model of the Curtiss XSB2C-1 airplane.

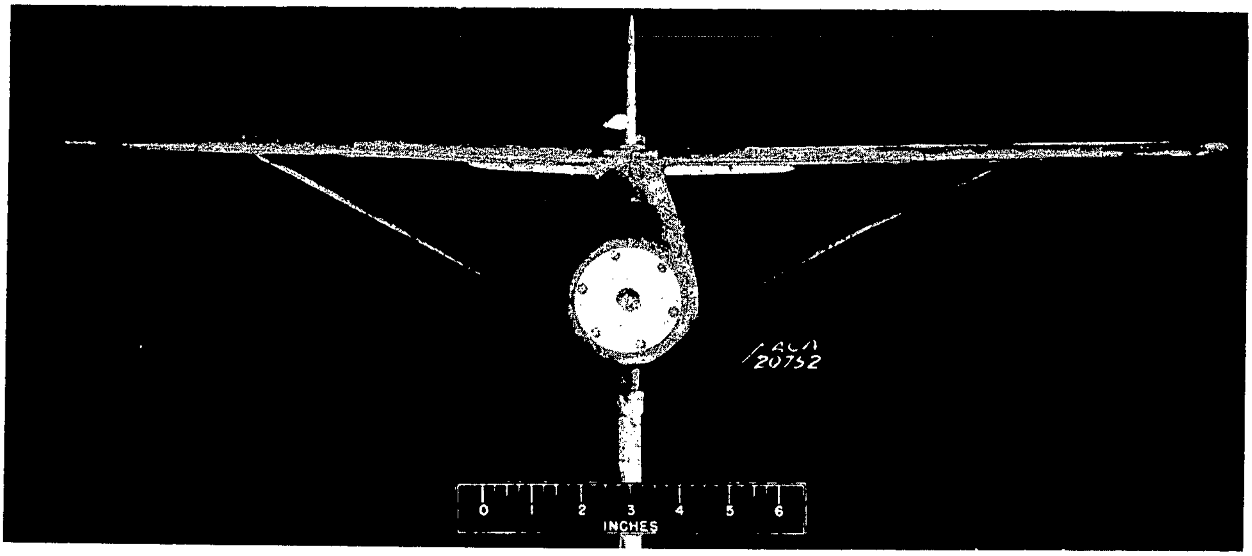


Figure 3.- Model 3. A 1/20-scale model of the Curtiss O-52 airplane.

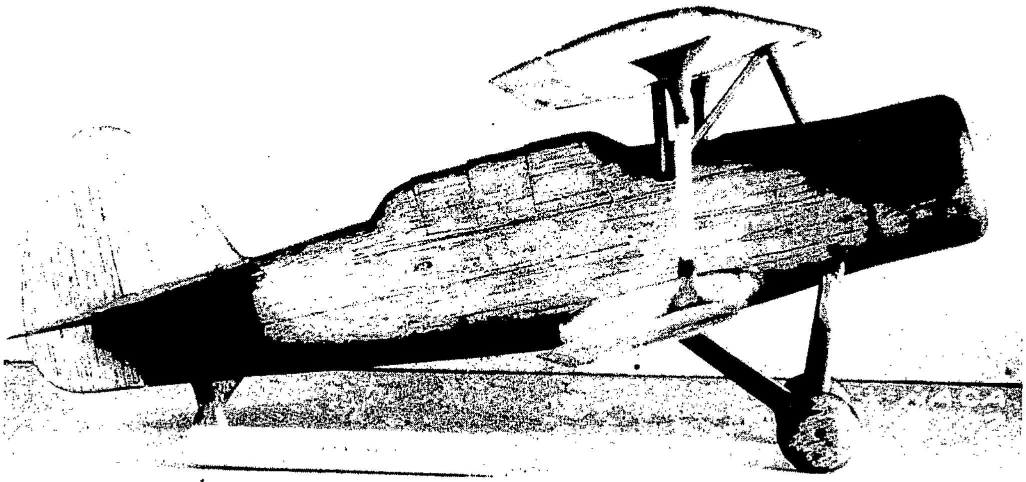


Figure 5.- Model 5. A 1/16-scale model of the Naval Aircraft Factory XOSN-1 airplane.

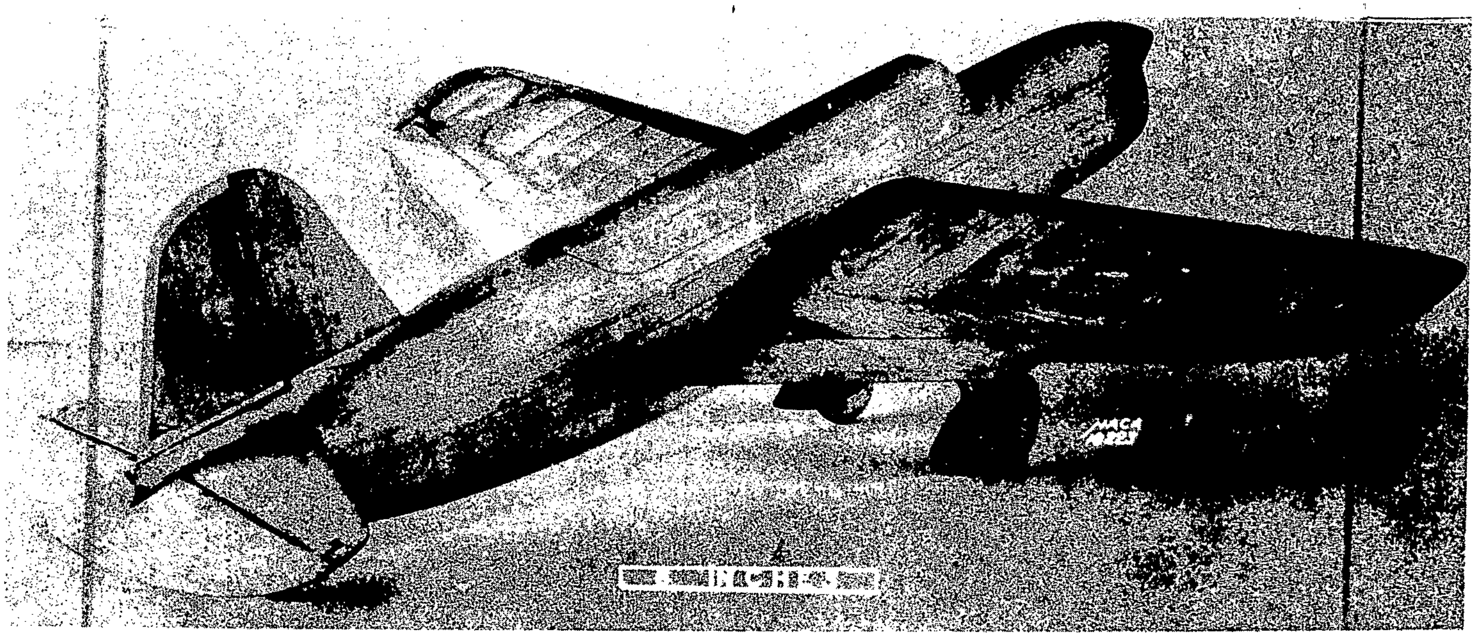


Figure 4.- Model 4. A 1/14-scale model of the Curtiss XSO3C-1 landplane.

(1 block = 10 divisions on 1/25" Eng. scale)

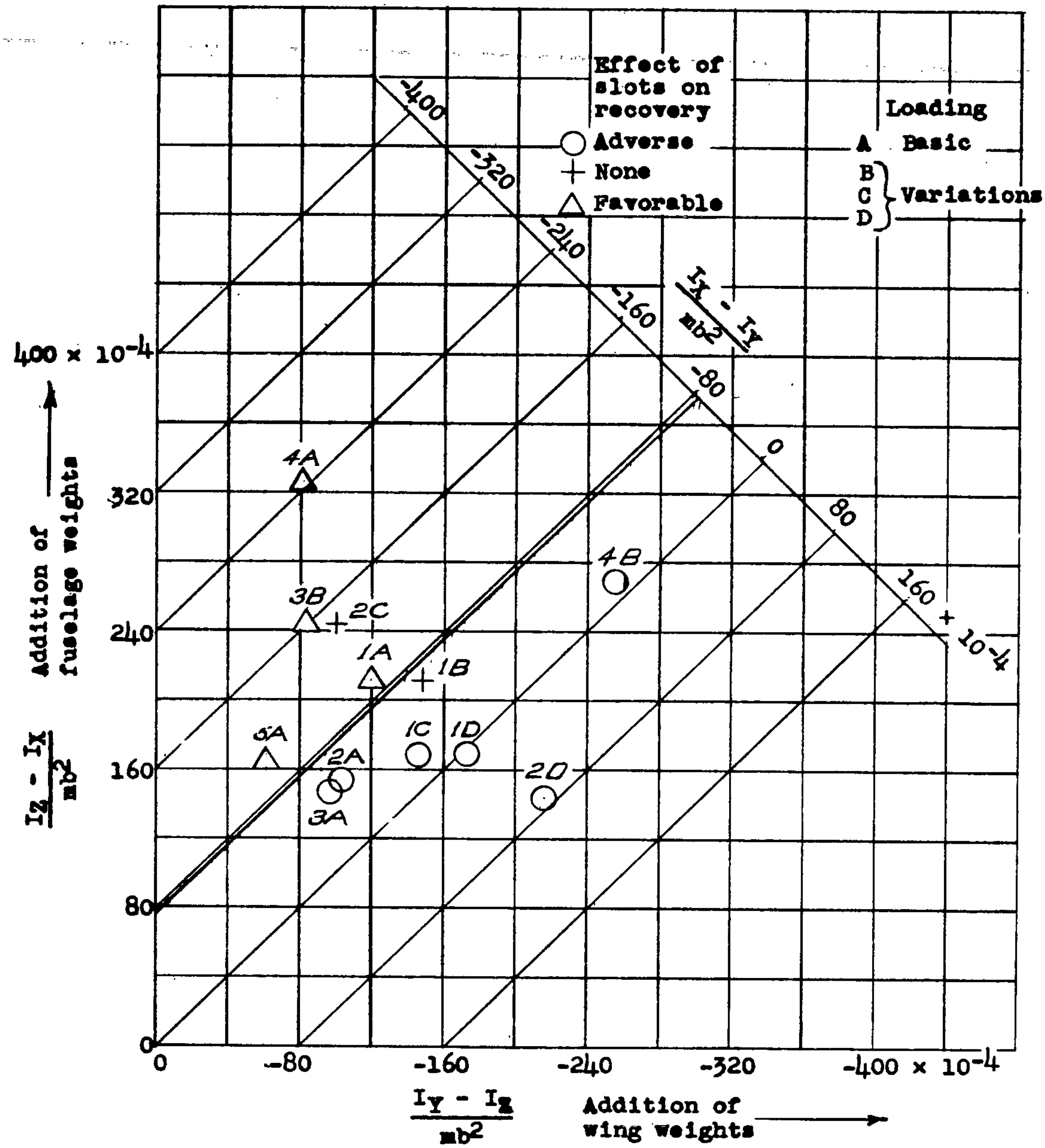


Figure 6. - Separation of slot effect by means of several mass-distribution parameters. All spins with ailerons and elevator neutral.